

# STATUS AND TRENDS IN MAGNET POWER CONVERTER TECHNOLOGY FOR ACCELERATORS

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## Abstract

Power converters (PC) is one of the key technologies for accelerators. During recent years with the development of power semiconductor devices, optimization of topologies, and improvement of manufacturing, the voltage and current ratings and power densities have greatly increased for PCs. Various PCs are required for various magnets in accelerators, but in principle the design for main topologies and the methodology for stabilizing the output are similar. Main topologies, digital control systems, and considerations for the future about the magnet PC are briefly discussed in this presentation.

## INTRODUCTION

In accelerator applications, all the energy used to accelerate or steer and stabilize the particle beams are supplied by numerous PCs. Many PCs are commercially available, but generally they can't be used directly because of the special requirements such as very low ripple, very high precision, a large range over current and voltage, and sophisticated control and interface. The PCs are normally custom designed for accelerators.

## TOPOLOGIES

There are three main power converter topologies that are widely used for accelerators: linear power converter (LPC), SCR power converter, and switch-mode power converter (SMPC).

### LPC

These power converters were extensively used several decades ago. As an example, for BEPC (built in 1988, and upgraded to BEPCII in 2004), LPCs occupied 85% of the total number. There are a few drawbacks of this topology:

- Big size: because of the line-frequency transformer, large LC filter and regulation transistor bank.
- Low efficiency: continuous dissipation of excess power in the regulation transistor bank.

Since the transistors operate at linear range, the regulation noise level of a LPC is low and output ripple is small. And based on the regulation principle, a LPC has an excellent transient response as well. Now the LPC is usually designed for magnetic field measurements at labs for reasons of its low ripple output. For fast correction magnet PCs, linear topology is used benefiting from its high bandwidth and fast response.

### SCR

This topology is still widely used for high power applications above hundreds of kW. For bending magnet PCs of storage rings, SCR is always a reasonable solution, e.g., for LHC MB with ratings 13kA /  $\pm 190V$ .

The SCR is unsuitable for low power application because of its large and heavy magnetic components such as the transformers and chokes. For higher output powers and improving input current harmonics, the 12-pulse or more pulses rectifier design can be utilized. For lower ripple and better regulation dynamics, active filters can be installed by adding a linear regulator or a switch-mode PC in the main circuit. The bandwidth is low or at best moderate which is dependent on the number of pulses.

The power factor of the SCR power converter changes according to the variations of the firing angle  $\alpha$ . In order to keep the power factor as close to unity as possible, reactive power compensation circuits may be needed.

### SMPC

For magnet PCs of modern accelerators, whether under construction or in operation, the topology of switch-mode power converter has been extraordinarily developed and their popularity has greatly increased. The pulse-width-modulated (PWM) SMPC became very common ten years ago in the area of medium power usually up to hundreds of kW. With the development of semiconductor power devices especially the IGBTs, the SMPCs for high power applications up to MW are achievable.

The SMPC provides significant reduction of size and weight compared to a LPC or SCR resulting from the use of magnetic components with better character at high frequency, smaller output filters due to the higher corner frequency and the higher power density of modern power devices. And for this topology the regulation dynamics are very good as well due to the high switching frequency.

In order to achieve the high power, modules connected in parallel or series are commonly implemented. The current and voltage sharing between modules should be taken into account and designed carefully.

The multi phase-shifting technology has been developed to raise the switching frequency without compromising the efficiency. By PWMs phase-shifting for power modules, the equivalent operation switching frequency of the converter increases as many times as the number of the interleaved modules. The size reduction of magnetic components and filters, and the better regulation dynamics will be obtained.

The switching loss is considered as a major hindrance to maximizing the switching frequency. The topology named soft-switching was proposed in the nineties. The

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most prominent one is the full-bridge ZVS (Zero Voltage Switching) that employs constant-frequency phase-shifting control, which has been widely promoted for magnet PCs for accelerators. The following sections will present a few examples related to these technologies.

**CSNS painting magnet PC.** The China Spallation Neutron Source (CSNS) is designed to accelerate proton beam pulses to 1.6 GeV at 25 Hz repetition rate, striking a solid metal target to produce spallation neutrons.

To minimize the space charge effect and control the emittance of the beam, painting injection method is selected, and the painting PCs need controlling the output current at falling period accurately. The difficulty focuses on the high slew rate and high peak power however much lower average power. The following shows the specified parameters.

- $I_N > 18\text{kA}$ ,  $V_{\text{peak}} 3150\text{V}$ .
- Rising time: 1000us; falling time: 300~500us; flat time 50us; falling tracking error: better than 2%
- Max. falling rate: 260A/us
- Repetition rate: 25Hz
- Magnet impedance: 12uH/1.68mOhm

The modular approach is implemented as the Fig.1 shows to get the high current and voltage requirements.

There are ten identical power modules connected in parallel. In each power module, there are five H-bridges connected in series, and each arm of the H-bridge comprises four IGBTs connected in parallel directly. With interleaving the PWMs, the final equivalent operation switching frequency is up to 1.8MHz, which significantly speeds up the response time and greatly reduces the size of output filter.

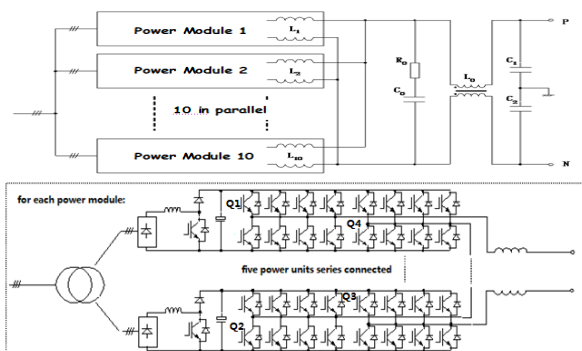


Figure 1: Block diagram of the painting magnet PC.

A booster circuit is employed at each of diode rectifier output stage to raise the module power factor, and to depress the harmonic components which transmitted to the grid from the module. Combined with the capacitor-storage system, the huge power variation is disposed of inside the power converter, and much smaller power fluctuation is seen from the grid. A buck chopper plus storage-capacitor bank is popularly utilized for this

situation as well, and the following example will describe in detailed.

Besides the outer current loop and the inner current-sharing loop, a specified current feed forward is added to speed up the response time.

**PC for slow cycling machines.** For a slow cycling machine, such as the AGS Booster Synchrotron at BNL, operating at 0.3~7.5Hz, the power supply is fed directly from the grid. Main magnet power supply is a 24-pulse thyristor control supply, and the peak power is 18 MWatts which is seen directly at the incoming ac line.

With the development of magnet power converter technology, advances in power electronics components, and developments in capacitor technology, medium-sized synchrotrons with cycling times of 1~5Hz take advantage of these developments for the solution of the magnet PC. The main topology is a switch-mode power supply, and energy is stored in capacitors. The implementation was pioneered at SLS, and similar schemes are also used or proposed for ANKA, ALS, DIAMOND, SOLEIL, CANDLE, SESAME and SSRF etc. booster synchrotrons. Fig.2 shows the scheme of the PSI 3Hz 1MWpeak bending magnet power converter.

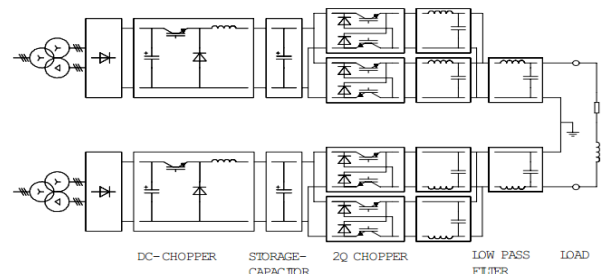


Figure 2: Scheme of the PSI booster bending magnet PC.

During the conduction mode, energy transfers from the storage-capacitor through the 2Q choppers to the load. During the inversion mode, current through the magnets finds its way through the diodes of the 2Q choppers and charges the storage-capacitor bank. Care should be taken to ensure proper current and voltage sharing between the similar power modules.

The capacitive energy storage system with switch mode control has been widely used benefiting from the development of power IGBTs. The high frequency inverter chopper controls both the direction and the flow rate of energy between the capacitor and magnet. At present it is only possible in the repetition rate of a few hertz for reasons of limited capacitor and IGBT voltage ratings. For higher cycling frequency, the inductive storage systems are still commonly used.

**PC for fast cycling machines.** For fast cycling PC systems with repetition rate greater than 10Hz, the standard circuit named 'White Circuit' is widely used. The energy is stored in the resonant network, consisting

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of the magnet inductance, resonant choke and capacitor bank. Based on the white circuit, the PC supplies the losses dissipated in the resistive part of the magnets, chokes and capacitors which are much lower than the cycling power needed. So the power converter can be designed to be much smaller.

The Rapid Cycling Synchrotron (RCS) of CSNS operates at 25Hz. For the RCS main magnets, there are totally six families' power converters, one for bending magnets, and five for quadruple magnets. Fig.3 shows the resonant network of the CSNS RCS bending magnet power converter (BMPC). There are totally 24 bending magnets. The resonant network comprises of 12 resonant cells connected in series. Each resonant mesh consists of two magnets, one choke and one capacitor bank. The excited power is supplied by one combined power converter with DC biased 25Hz AC (sinusoidal wave) current output which promises the current is always positive. The BMPC is based on PWM switch-mode design, with the output current of  $1350 + 970\sin(\omega t)$ , the voltage peak 6kV, the power peak 13.9MW, and the power average 2.4MW. The circuitry mainly comprises of five step-down transformers, ten diode rectifiers, and ten PWM H-bridge inverters connected in series.

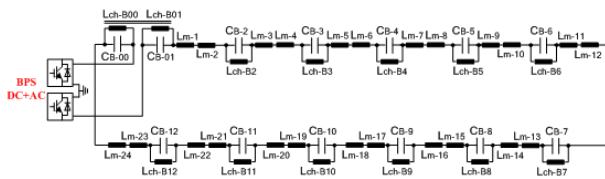


Figure 3: Resonant network of the CSNS RCS BMPC.

How to control the tracking error of cycling currents, the ultra high accuracy and stability of steady or slow-ramping currents, it is a challenge for present and future projects and mostly determined by the control system of the power converter.

## CONTROL SYSTEM

The control system of the early power converters in accelerators is analog. Here gives a brief summary of the analog electronics:

- mature, used many years and extensively developed
- if any changes of the PID parameters, manual hardware modification has to be done; if any major changes of the control system, the regulation hardware has to be redesigned
- the performance of the regulation is mainly dependent on the DAC and the DCCT
- not convenient for diagnostics

For a long time, since the introduction of a variety of digital signal processors, such as MCU, DSP and FPGA, it is possible to replace analog regulation functions like PID controllers by digital algorithms implemented in these intelligent processors. The advantage of digital control over analog includes:

- complex though fast control algorithms can be implemented and remains stable in relation with the process dynamics
- flexible for different projects
- no extra offset or drift, better noise immunity
- parameters optimization and even changes of the control system can be done by software, no redesign required
- friendly for debugging and diagnostics
- easy to extend functionality

For a digital control system, the performance of the converter is mainly determined by the ADC (for the current sampling) and DCCT. Some modern accelerators like LHC and SLS have made major advances in the area of “digital controlled PCs”. The approach of LHC is that they only apply their digital controller for current regulation. The philosophy is to have a “universal” current controller, which can drive “a variety of standard voltage sources”. These voltage sources vary between “switched mode power supplies” and “classical thyristor converters”, all with internal voltage control. The algorithm of a tri-branched structure known as the RST structure has been developed and implemented perfectly in the digital current controller of LHC PCs. With the RST controller, the desired tracking behavior (following the reference) is obtained independently of the desired regulation behavior (rejection of a disturbance). This method provides a good tracking of the reference with no lagging or overshoot.

The current control loop is designed to make the complete system behave like a “perfect” current source, reaching a very high precision (a few ppm) even in the case of very large load time-constants. Fig.4 shows the principle scheme of the RST controller.

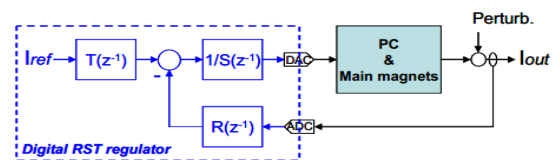


Figure 4: Block diagram of the RST controller.

The following will show an example of FPGA-based digital controller and its implementation for the project CSNS. The commercial lifetime of almost any existing hardware design is shortened drastically caused by the stormy developments of FPGA. This especially is true for designs that use non-FPGA hardware as their processing core, since these “application specific components” often are programmed with device-specific code, making the software design less portable to new hardware components when obsolete items have to be replaced.

Digital Power Control Module (DPSCM) is specially designed for accelerator magnet PCs at IHEP. There is only one FPGA fulfilling the fully-digital control, and the design principle of system on a programmable chip (SOC) has been implemented. The DPSCM can be

embedded in the switch-mode or the SCR PCs. The power converter system for the project CSNS is fully-digital, not only for the DC PCs, but also for the white circuit resonant PCs. The following shows the control strategy for CSNS resonant PCs, the method of harmonic vector-injection has been developed in the FPGA of DPSCM for promising the sinusoid magnetic field.

The PC prototype is designed to supply a sinusoidal current as pure as possible at first. With normal PIDs, it is very difficult to control the current tracking error for cycling output, the higher the frequency the more difficult for the reason of the limited gain at the dedicated resonant frequency. The repetitive controller and the harmonic analyzer have been designed in the DPSCM, and it proves that the current tracking error can be controlled to be lower than 0.1% with a resistive load.

After debugging with the bending and quadruple magnet prototype, serious magnetic saturation was found during the 25Hz cycling period. The non-linearity of dynamic inductance of BM is approximately 14%, QM about 7%.

If the current is designed to be as pure sinusoidal as possible, the output voltage increases dramatically to compensate the magnetic saturation.

Consequently the control strategy for the resonant PC changes from pursuing the pure sinusoidal current output to as likely sinusoidal magnetic field as possible. Fig. 5 shows the principle of the control method.

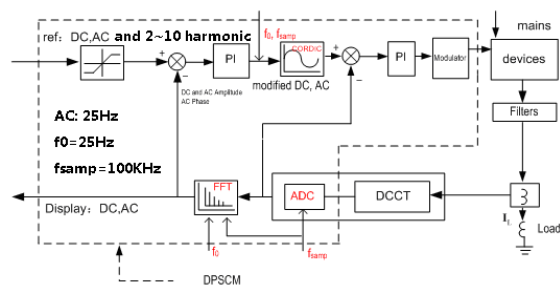


Figure 5: Digital controller for CSNS RCS resonant PCs.

Basically there is a requirement that the dc and 25Hz ac amplitude and phase of the current should be controlled as desired value as possible. So there are three additional PIs for close-loop control of dc amplitude, the fundamental ac amplitude and phase. The reference is not a pure sine wave anymore, but a modified waveform based on the above PIs. For decreasing high order harmonic magnetic fields, the harmonic vector-injection is embedded into the digital controller. The high-order harmonic (2~10) currents are added manually to create high-order harmonic magnetic fields, which are the same amplitudes but phases reversed compared to the fields produced by the 25Hz ac current.

The tracking of the current between bending and quadruple magnets is important to the operating performance of the RCS because of the narrow margin for the tune shift. For RCS the phase is required to be tracked within 1us (0.009deg). For most cycling systems, for

example BESSY II, SRRC booster synchrotrons and JPARC RCS, the phases of the focusing quadruples and the defocusing quadruples are referenced to the current phase of the bending magnets.

For CSNS totally six families, each is a combined ac plus dc PC, i.e., the output current is exactly what the magnets see. With the close-loop control, the phase will track the reference phase (triggered by the timing system) exactly. Therefore each PC will follow its phase reference individually, and the original differences of phase delay between six families, which are determined by the test results of magnetic field measurements, can be compensated through the triggers.

## CONSIDERATIONS

The fully digital control system is already a trend for magnet PCs in accelerators.

### “Digital” DCCT

If a “digital” DCCT could be designed with the same speed and accuracy as the analog counterpart, this would provide far greater flexibility and convenience in the control system of a PC. At Femilab, a world’s first digital DCCT used in the beam instrumentation has been developed. Although the requirements for two systems are different, the principle is almost the same. The news gives us some inspiration on the digital DCCT for digital power converters.

### Communication System

It is now an integral part of the digital controller. Here shows the considerations for the communication design:

- more close working with accelerator control people
- solutions should be easy to develop, easy to interface, simple architecture, reliable, advanced in the future
- interface with timing system to accept global timing/event triggers
- strong integration in the particle orbit feedback system, providing a deterministic communication between systems
- fiber connection recommended to reduce EMI affect for the low voltage electronics circuits

### Control Algorithm

Based on the methods of digital signal processing, there are many algorithms besides classical PID that can be developed and implemented.

- many types of optimized PID controllers
- repetitive controller, useful for cycling output control
- harmonic analyzers applying modern signal processing methods such as wavelet analysis, notch filters and etc.
- adaptive state controller, optimizing parameters during operation
- artificial intelligence technology for example expert systems embedded into the digital controller for better diagnostics, faults analysis and location
- any other creative ideas



## Application of ADCs

The ADC which is responsible for measuring the output current, it is a very important and temperature sensitive component for a digital control system. For the ongoing requirements of higher and higher stability and accuracy, the choice and application for the ADC is very critical for the performance. It is necessary to get a balance between the resolution, speed and cost. Specifications such as internal/external reference, linearity and latency etc, need to be taken into consideration for a most appropriate choice for your projects. It is very true that we can never underestimate the difficulties in realizing the datasheet promises. Considering the great demands on long-term stability, a temperature control oven for the ADC and its peripheral circuits is strongly recommended.

About the power parts, the system reliability, EMC considerations, the trend of higher and higher voltage, current and power requirements for future projects and combined PCs are briefly presented as follows.

### System Reliability

For efficiency and operation space considerations, some power converter systems are required to be installed underground. Under normal conditions, the system could work with a MTBF of several years. The system reliability is required to be very high. More solutions could be taken into considerations:

- Redundancy design: a power converter with a built-in redundancy by a modular approach. The power part is divided into  $n + 1$  module,  $n$  supplying nominal current, and one module will work in case of trip. Automatic 'hot' switching between modules is needed.
- 'hot' maintenance and repair
- Efficient monitor and diagnosis method to prejudge the problem appearance.
- Mains stability is required. The mains voltage sags correction devices and UPS might be needed.

### EMC Considerations

The power converter EMC character is a considerable factor to affect its high precision and high stability performance. The power supply system EMC design should be conducted under the EMC principle of accelerator facility. The design work of PC EMC should be coordinated with: the design of various equipments distribution, the electricity mains distribution and grounding, the design of overall facility grounding, and the design of cabling, especially the cabling for magnet loads and mains.

- The PC equipment EMC design should be conducted at early stage, strengthen the EMC studies for converter prototype.
- Converter topology design: Choose soft switch (ZCS/ZVS) for switch mode converter. Choose digital PS controller instead of analog one. Use

photo-fiber for signal long distance transmission. The decouple circuit among the DC-DC converters which are supplied by one common voltage converter.

- The PC mechanical and electrical technology: prevent EM emission leakage, obstruct the EM coupling path, and strengthen the immunity of sensitive elements. The works include: elements distribution, PCB design, cabling, shielding design, grounding, filter and snubber design, installation etc.
- Preventing any accidental connection between converter grounding bus and the power grid nature line to avoid mains current pass through PC grounding bus. The power parts and low level control parts should use separated low impedance cables to grounding bus.

### Combined PC

In some cases, a combined PC might be a good choice to achieve the accelerator requirements. For example, a low power LPC could be combined with a high power SCR or SMPC, the both of output current are added to feed common load. Under the control according to a cooperation mode, the LPC could get high response speed in local output range while the SCR/SMPC operates at high power level. This combined PC could avoid large size and low efficiency since the LPC is employed at low power.

### High Voltage, High Current, High Power System

The switch-mode power converters will be more widely used for high power equipments. Several MW even a few tens MW can be achievable for this type converters. High power semiconductor devices and new system topologies are continuously improving for achieving higher power, improved efficiency and reliability and better controllability.

- Modular approach: power modules in series and parallel to get the high voltage and high current requirements.
- Mutli phase-shifting: get a high equivalent frequency, then to reduce the size of output filters, and get a better regulation dynamics.
- Power semiconductor devices: the most important factor which determines the power converter technology in accelerators. There are a lot of ongoing developments that make it possible to appear new and better semiconductors in the near future.

The modern magnet power converter technology has blended together the technology of electronics, power integration, automatic control theory, circuit theory, digital signal processing, electromagnetic compatibility, materials, sense, thermal engineering etc. Power electronic engineers will experience more challenges, more professional commitments, and will enjoy great funs as well.

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